AN ELECTRICAL THRUST VECTOR CONTROL SYSTEM FOR THE VEGA LAUNCHER

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ABSTRACT

This paper presents the thrust vector control systems designed and currently under qualification for the four stages of the European launcher VEGA. Special attention is given to the design and qualification of the electro-mechanical actuators.

1. KEY WORDS

Thrust Vector Control (TVC), Electro-Mechanical Actuator (EMA).

2. SYMBOLS AND ABBREVIATIONS

AC	Alternating Current
ADC	Analogue Digital Converter
BS	Battery Set
DC	Direct Current
DCM	Digital Control Module
DFF	Dynamic Force Feedback
EMA	Electro – Mechanical Actuator
HBRISC	Hardened Bi-RISC processor (SABCA proprietary)
HW	Hardware
IPDU	Integrated Power Distribution Unit
OBC	On Board Computer
PM	Power Module
PWM	Pulse Width Modulation
SW	Software
TLM	Telemetry
TVC	Thrust Vector Control
VEGA	Vettore Europeo di Generazione Avanzata

3. INTRODUCTION

The aim of the TVC is to control the flight of the launcher by controlling the direction of thrust. It is a nested loop (small loop) inside the launcher attitude control (*figure 1*).

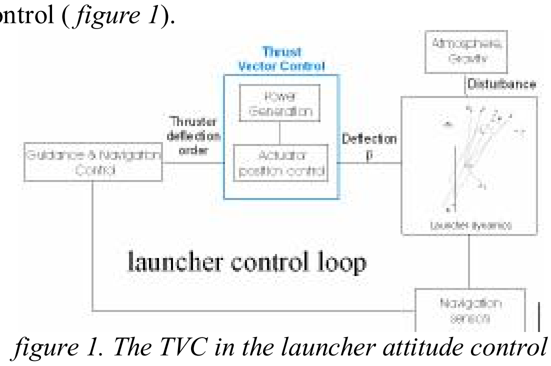

figure 1. The TVC in the launcher attitude control

SABCA has developed and is qualifying the TVC system for the four stages of the European launcher VEGA. The VEGA launcher consists of 4 stages called P80, Z23, Z9 and AVUM. (*figure 2*) The TVCs are optimised while keeping the same architecture. Each TVC system consists of two Electro-Mechanical Actuators (EMA), one piloting electronics, called the Integrated Power Distribution Unit (IPDU), the electrical power generation via a Battery Set (BS) consisting of Li-ion battery module(s) and the relevant cable harness for power distribution and telemetry between the Battery, IPDU, EMA and Telemetry (TLM).

This paper presents the architecture of the TVC and the design and testing of the EMAs in the framework of the Vega TVC development and qualification.

figure 2. VEGA launcher

4. TVC design

The TVC system consists of (*figure 3-figure 4*):

- A pair of EMAs connected between the aft skirt of the stage and the nozzle attachment point. Two EMAs, set at 90°, allow controlling the launcher trajectory in yaw and pitching by controlling the direction of thrust. Through coordination of the elongation and retraction of the two EMAs, the thrust can be directed as needed to control the movement of the launcher. The EMAs are controlled by the IPDU.
- An IPDU receiving the deflection order from the On Board Computer (OBC) through a 1553 digital bus, distributing the battery power to both EMAs and ensuring the digital control of the TVC.
- A set of several battery modules able to deliver the required power during the mission.
- A cable harness for power distribution and telemetry between the Battery, IPDU, EMA and Telemetry (TLM).

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There is no redundancy in the TVC system and the reliability is based on the quality of the components.

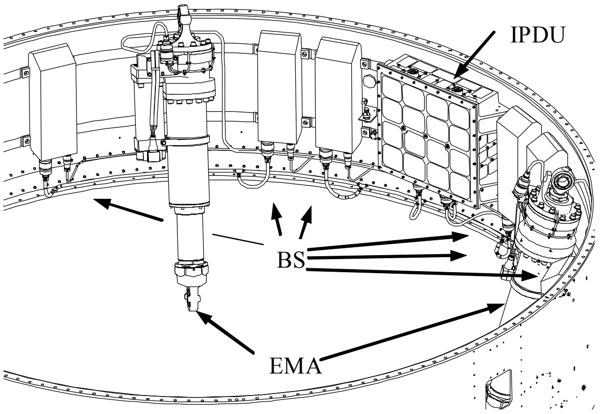

figure 3. The P80 TVC system

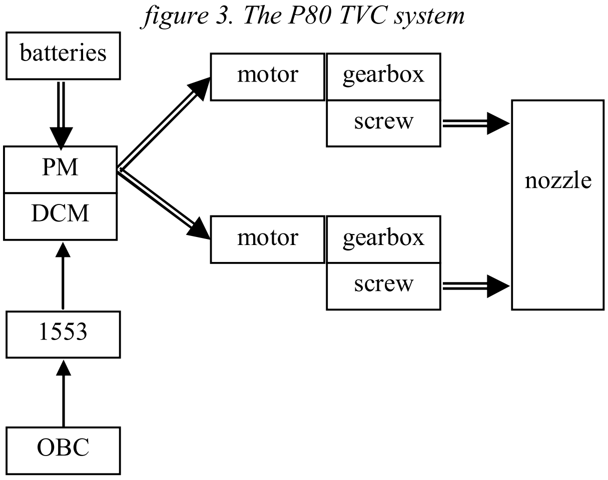

figure 4. TVC architecture

The TVC architecture is the same for the four stages. With this architecture the performances of *Table 1* are reached.

Table 1: TVC performances

Parameter	1st stage	2nd stage	3rd stage	4th stage
Input power [kW]	51	15	5	1.2
Output power [kW]	2 x 16	2 x 5.4	2 x 1.1	2 x 0.14
Min voltage [V]	270	135	45	45
Max voltage [V]	410	210	75	75
Flight duration [s]	120	275	395	4060
Stall force [kN]	100	30	20	2.5
No-load speed [mm/s]	400	275	125	80
Bandwidth [Hz]	8	8	3.5	3.5
Pin-to-pin length at null [mm]	1048	642	642	251
Full stroke [mm]	340	225	225	72
Environment				
TVC temperature [°C]	-20/70	-20/70	-20/70	-20/70
Battery temperature [°C]	10/60	0/70	0/70	0/70
Random vibration [g_{RMS}]	20	20	20	20

4.1. IPDU

Each VEGA TVC electronics (*figure 5* - *figure 6* - *figure 7*) consists of two main functional components:

- the IPDU hardware (HW)
- the TVC Software (SW) implemented in the Digital Control Module (DCM.)

The IPDU SW is automatically generated from the control algorithm which is implemented in Matlab-Simulink®, as well as the motor model and all the interfaces. [4] This approach allows the developer to use the same implementation to perform simulations and to generate the code for the HBRISC2 processor. It has the double advantage of shortening the development time, and increases the reliability. In this way, SABCA has developed and qualified the TVC software for the four stages of the VEGA launcher.

The IPDU HW contains two functional modules (*figure 4*):

- one controller module, called Digital Control Module (DCM)
- one power distribution unit, called Power Module (PM)

The power distribution unit and the DCM are integrated in a single physical box that is called "Integrated Power Distribution Unit" (IPDU).

figure 5. A photograph of the first stage electronics: P80 IPDU

figure 6. A photograph of the second and third stages electronics: Z23 / Z9 IPDU

figure 7. A photograph of the fourth stage electronics: AVUM IPDU

The DCM receives the position order from a single 1553B bus coupling function from the OBC, unique to the two lanes. It performs, for each lane, using ADC, synchronous acquisition of:

- the two EMA electrical motor currents (from Hall effect transducers)
- the EMA motor angular position (from resolver)
- the EMA position (from LVDT)
- the IPDU power bus current (from Hall effect transducers)
- the IPDU power bus voltage (from analogue isolation amplifier sensor)

The DCM also implements the closed loop control of the TVC through the SW uploaded in a highly secured processor called HBRISC2 [4] qualified for space applications. The DCM converts the position order into control voltages to PM inverters and it digitally implements the control strategy which consists of a current loop, speed loop and position loop (with DFF for the first stage only).
The DCM also provides the necessary telemetry to the launcher.
The DCM is supplied with 28 Vdc provided by the Multi Functional Unit (MFU) of the launcher.
A design constraint for the VEGA IPDUs was to use the same DCM on the four different stages in order to maintain this communality and reduce development costs.

The PM receives the necessary DC power from the battery set through a power switch (for the first three stages) and delivers the AC power to the EMAs in a controlled manner.
The main components of the PM are the following:

- IPDU power switch: the power switch can be opened or closed on ground in order to enable or disable power transfer. This switch function is not present in the fourth stage IPDU because this function is performed by the MFU.
- RC Power filter: the input stage of the IPDU ensures the electric stability of the IPDU whatever the IPDU and motor operating point, it reduces the ripple of the bus voltage and the conducted emissions on power lines.
- The power bus measurements allow the measurements of the bus voltage and currents. These signals are used for telemetry purposes and power switch activation when the IPDU is in a secure mode.
- Isolated driver power supply and power inverters: the electrical motor is controlled by pulse width modulation voltage control (PWM). With PWM voltage control, the inverter switches are used to divide the quasi-sinusoidal output waveform into a series of narrow voltage pulses and modulate the width of the pulses to control the speed of the motor. The drivers are supplied by the isolated driver power supply.
- Current sensors: are installed to measure the currents of the power lines.
- Temperature sensors: are installed to measure the invertors and the DCM temperatures.

The Z23 and Z9 IPDU hardware (*figure 6*) is common; however the SW parameters are optimised for each stage. The P80 IPDU is tight to avoid any corona risk.

4.2. Cable Harness

Though often forgotten, another important part of the TVC is a complete cable harness connecting the different TVC elements together. The cable harness consists of power cables and data cables.
The power cables allow distribution of the power from the battery set to the IPDU and from the IPDU to the EMAs. The data cables distribute the LVDT, resolver and temperature sensor data from the EMAs to the IPDU and provide telemetry data from the batteries to the launcher.

4.3. Battery Set

For the VEGA application, the need for the first three stages is:

- High power, during a short time.
- Possibility of high reverse power in braking mode
- Low energy
- Possibility of recharge in case of launch abort
- Long wet life

For the fourth stage, the flight duration is longer and the energy need is higher.
Considering this need, SAFT VL8P lithium-ion cells have been selected for the first three stages and SAFT MPS176065 cells for the fourth stage.
15 VL8P lithium-ion cells connected in series result in the battery module presented in *figure 8* (left) for the first three stages.
The battery for the fourth stage (called ACTB) is an assembly of 15 rows of 3 strings of MPS176065 cells (total of 45 cells) and is presented in figure 8 (right).
The P80 stage consists of 6 battery modules, the Z23-stage of three and the Z9 and AVUM stage of one.
The performances of those batteries have been presented in [5].

figure 8. P80- Z23-Z9 battery module (left) and AVUM battery (right)

4.4. EMA

The electro-mechanical actuators for the first three stages of the launcher consist of a brushless permanent magnet synchronous motor that drives a roller screw through a gearbox. This way the rotational motion of the motor is transformed into a linear motion. (*figure 9*). The roller-screw / nut is in the configuration fixed screw - movable nut. The EMA piston is attached to the movable nut. This configuration has the advantage to protect the internal of the EMA and the screw against external pollution.

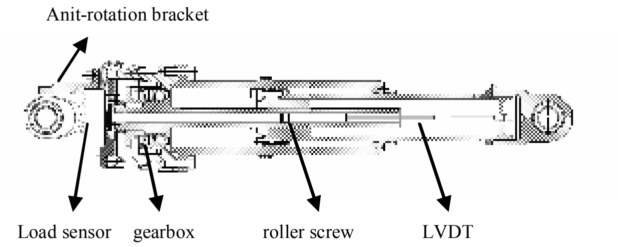

figure 9. cross section of P80 EMA

The EMA linear position is measured by an LVDT. The motor angle is measured by a resolver placed on the motor axis. An intrinsic characteristic of such design with respect to a hydraulic actuator is the high equivalent inertia with respect to the load (the nozzle). This is obviously inconvenient to damp the nozzle gimballing mode: if the load oscillates, the position controlled actuator follows with very small amplitude that cannot be measured by the integrated position sensor of the EMA. This is why a force sensor is introduced on the EMA of the first stage (*figure 10*) to detect the load oscillation. ([1] and [2])
A force sensor consisting of strain gages has been designed and integrated in the tailstock of the P80 actuator. It allows measuring the axial force transmitted by the actuator to the launcher structure (*figure 11*).

figure 10. A photograph of the first stage actuator: P80 EMA (250 x 350 x 1050 mm)

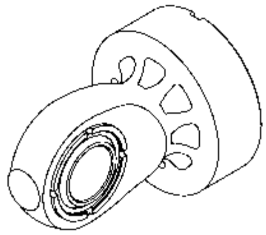

figure 11. Tailstock lug with integrated force sensor

A temperature sensor is placed inside the electrical motor. The EMA is installed using its two spherical bearings. An anti-rotation bracket and anti-rotation lugs are foreseen in order to eliminate the rotation of the EMA around its axis. The pin-to-pin length of the EMA can be changed by rotating the motor axis via a dedicated axis, or by using the pin-to-pin length adjustment capability on the rod end.
The electrical motor for the P80 presents a corona risk. [3] The stator was impregnated and moulded with an appropriate resin to eliminate this risk. In this way the electrical motor was assessed corona-free.
As for the IPDUs, the mechanical designs of the EMAs for the second and third stage (*figure 12*) are identical and are very similar to the one of the P80 (no load sensor). By software command the pin-to-pin length is adjusted to the ones required for Z23 and Z9.

figure 12. A photograph of the second and third stages actuators: Z23 / Z9 EMA (140 x 225 x 700 mm)

The fourth stage actuator is an existing actuator adapted to the needs for VEGA. This actuator contains a ballscrew in stead of a rollerscrew and has the configuration of fixed nut / translating screw. (*figure 13*).

figure 13. A photograph of the fourth stage actuator: AVUM EMA (96 x 170 x 251 mm)

5. EMA QUALIFICATION

The qualification process presented is the one for the P80 actuator. The principle is the same for the other stages. The EMA P80 will be subjected to the following qualification tests:

- Vibrations
- Thermal cycling
- Humidity
- Endurance
- Extended performances in cold and hot.
- Vacuum
- EMC

The Vacuum and EMC testing will not be discussed with this presentation.

5.1. Vibration

The EMA has been subjected to the sine vibration levels of *Table 2* and a random vibration of 20grms during 4 minutes for each axis. Sine survey testing has been performed before and after each test.

Table 2: Input sine vibration levels

Freq (Hz)	**Level X**	**Level Y - Z**	**Sweep rate**
5-16	10 mm	10 mm	1/3 oct/min
15-35	10 g	10 g	
35-70	22.5 g	12 g	
70-150	22.5 g	12 g	2 oct/min
150-200	22.5 g	22,5 g	
200-2000	10	10 g	

The measurements made before, after and during the vibration campaign did not reveal any anomaly. The EMA performances before and after the vibration campaign are identical.

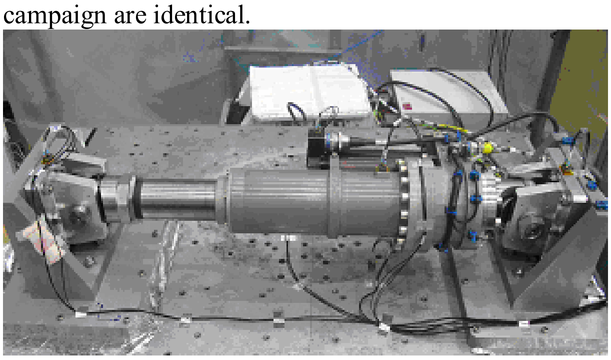

figure 14. A photograph of the P80 EMA installed on the shaker during qualification vibration.

5.2. Thermal cycling

The EMA P80 was submitted without interruption to 12 thermal cycles from -20°c to +70°C. The total test duration took almost 90 hours. During this thermal cycling qualification campaign, the EMA showed its ability to sustain the 12 thermal qualification cycles without any degradation of its measured performances. The measurements made before, after and during cycling don't show any abnormal behavior due to temperature solicitations. The EMA hasn't encountered any visual degradation and has successfully passed all the health tests after thermal cycling.

5.3. Humidity

The EMA P80 and the IPDU P80 have been put in a steam chamber together and have been submitted without interruption to 2 successive thermal cycles from +20°C to +35°C (see figure 2), with a constant humidity level programmed at 96.5% +/-3.5 % for a total duration of 50 hours. During this humidity qualification campaign, the EMA and the IPDU have shown their ability to sustain the 2 humidity qualification cycles without any degradation of their measured performances. The measurements made before, after and during cycling did not show any abnormal behaviour due to humidity and temperature solicitations. EMA and the IPDU have not encountered any visual degradation and have successfully passed all the tests after humidity test.

5.4. Endurance

The EMA P80 has been subjected to the endurance life cycle as presented in Table 3. In order to be able to load the EMA, the EMA has been installed in a tests bench representative of the nozzle flexible joint stiffness, nozzle inertia and attachment point stiffness.

Table 3: Endurance profile for P80 EMA

Cycle N°	% of max stroke	Frequency [Hz]	# Cycles	Duration (hours)	Displacement (m)
1	± 95	0,3	3700	3h 26min	1898.100
2	± 50	0,6	4800	2h 13 min	1296.000
3	± 30	1,0	5000	1h 23 min	810.000
4	± 10	2,0	7000	0h 58 min	378.000
5	± 5	5,0	8500	0h 28 min	229.500
6	± 5	3,0	1500	0h 08 min	40.500
7	± 95 (no load)	0,35	2500	1h 59 min	1282.500
TOTAL			33e+3	10h 35 min	5934.600 (±5.9 km)

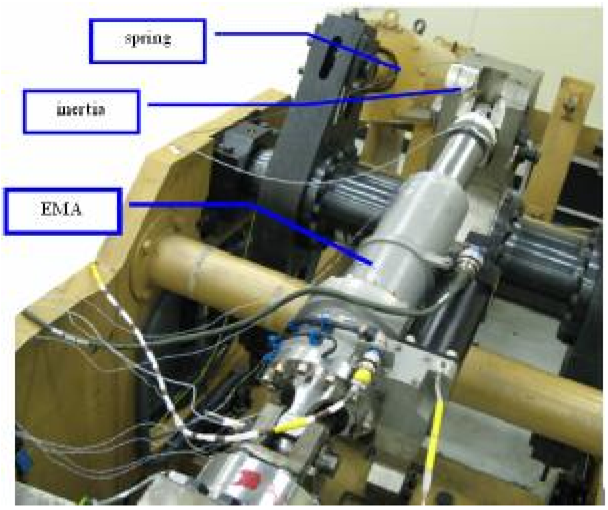

figure 15. P80 EMA installed in its load test bench

Detailed inspection by dismounting the EMA still has to be performed in order to determine that no mechanical degradation has occurred. However all testing before, during and after did not reveal any degradation of EMA performances.

5.5. Extended performances in cold and hot.

An extensive qualification campaign has been performed to characterise the performances of the EMA and IPDU combination in different operational conditions. The performances are characterised by changing the following parameters:

- ambient temperature between -20 °C and 70°C
- high power input voltage varied between 318V and 352 V.
- 28V low power input voltage varied between 24V and 32V.
- battery input resistance variation between 135mOhm and 325mOhm.

When varying these parameters, the performances of the system are measured. A very low variation of the performances has been measured with temperature and almost none with input voltage and input resistance. As an example the P80 EMA frequency response and EMA maximum step response are given in *figure 16* and *figure 17*. Other EMA performances that have been characterised are the EMA static accuracy, the EMA stall force, the time delay, the consumption during a typical flight duty cycle, backlash, reversibility and stiffness.

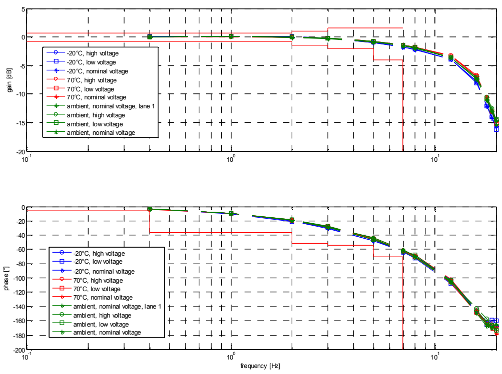

figure 16. P80 EMA frequency response at different temperatures with different input voltages.

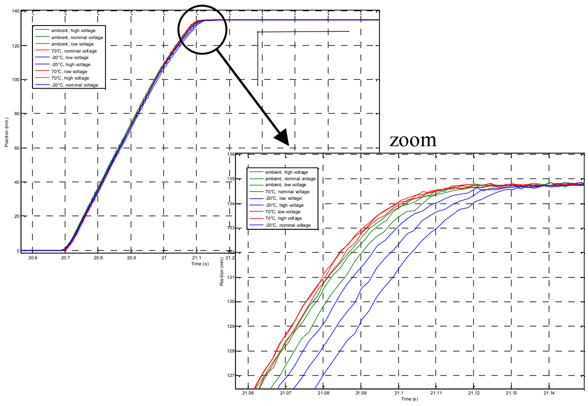

figure 17. P80 EMA maximum step response at different temperatures with different input voltages.

6. Conclusion

This paper presented the TVC system of the four stages of the VEGA launcher. The EMA design and qualification results have been dealt with more detail. The qualification results demonstrated the capabilities of the TVC system. The responsibility and mastery of the complete TVC system (mechanics, electronics, software and power generation) at a unique subcontractor has revealed during design and qualification phase several advantages:

- The possibility to analyse and apply changes in the best possible ways and in the best location (electronics, by software or hardware).
- The ability to combine (qualification) tests on different equipments.
- The ability to perform tests on sub level system (IPDU + EMA + cable harness + batteries).

7. References

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8. ACKNOWLEDGEMENTS

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